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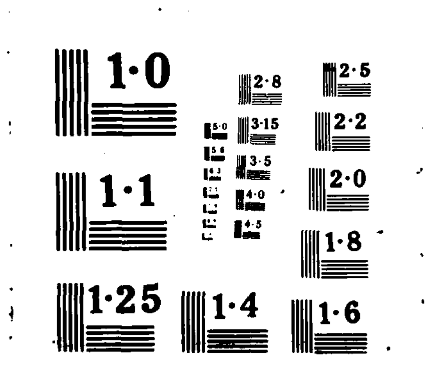
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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): TELAC Report-[illegible]	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 86-0892
6a. NAME OF PERFORMING ORGANIZATION: Technology Laboratory for Advanced Composites, Massachusetts Institute of Technology / 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: AFOSR/NA
6c. ADDRESS (City, State and ZIP Code): M.I.T.; Room 33-309, 77 Massachusetts Ave, Cambridge, MA 02139	7b. ADDRESS (City, State and ZIP Code): Bolling AFB DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AFOSR / 8b. OFFICE SYMBOL (If applicable): NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: AFOSR 84-0140
8c. ADDRESS (City, State and ZIP Code): Bolling Air Force Base, Washington, DC 20332-6448	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO.: 61102F; PROJECT NO.: 2302; TASK NO.: B1; WORK UNIT NO.:
11. TITLE (Include Security Classification): Dynamics and Aeroelasticity of Advanced Composites	
12. PERSONAL AUTHOR(S): John Dugundji & Gun-Shing Chen	
13a. TYPE OF REPORT: Final Report / 13b. TIME COVERED: FROM 5/1/84 TO 6/30/85	14. DATE OF REPORT (Yr., Mo., Day): 1986 March 1 / 15. PAGE COUNT: 25
16. SUPPLEMENTARY NOTATION	
17. COSATI CODES: FIELD / GROUP / SUB. GR.	18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

An analytical and experimental investigation was made of the aeroelastic flutter and divergence behavior of graphite/epoxy forward swept wings with rigid body pitch and plunge freedoms present. A complete, two-sided 30-degree forward swept wing aircraft model was constructed and mounted with low friction bearing in a low speed wind tunnel. Four different ply layup wings could be interchanged on the model, namely, $[0_2/90]_s$, $[15_2/0]_s$, $[30_2/0]_s$, and $[-15_2/0]_s$. Wind tunnel tests on the "free" flying models revealed body freedom flutter, bending-torsion flutter, and a support dynamic instability which could be eliminated by proper adjustment of the support stiffness. Good agreement with linear theory was found for the observed instabilities.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED X SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL: ANTHONY K AMOS	22b. TELEPHONE NUMBER (Include Area Code): (202) 767-4937	22c. OFFICE SYMBOL: AFOSR/NA

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DYNAMICS AND AEROELASTICITY OF COMPOSITE STRUCTURES

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March 1986

Final Report for Period: 1 May 1984 - 30 June 1985

AFOSR Grant: AFOSR-84-0142

ABSTRACT

An analytical and experimental investigation was made of the aeroelastic flutter and divergence behavior of graphite/epoxy forward swept wings with rigid body pitch and plunge freedoms present. A complete, two-sided 30-degree forward swept wing aircraft model was constructed and mounted with low friction bearing in a low speed wind tunnel. Four different ply layup wings could be interchanged on the model, namely, $[0_2/90]_s$, $[15_2/0]_s$, $[30_2/0]_s$, and $[-15_2/0]_s$. Wind tunnel tests on the "free" flying models revealed body freedom flutter, bending-torsion flutter, and a support dynamic instability which could be eliminated by proper adjustment of the support stiffness. Good agreement with linear theory was found for the observed instabilities.

FORWARD

This report describes work done at the Technology Laboratory for advanced Composites (TELAC) at the Massachusetts Institute of Technology for the Air Force under Grant No. AFOSR-84-0142. Dr. Anthony K. Amos was the contract monitor.

The work reported herein was performed during the period 1 May 1984 through 30 June 1985. The work represents the efforts of one graduate student Gun-Shing Chen, and one undergraduate student, Karen Needels, under the direction of the Principal Investigator, John Dugundji, and the supporting laboratory staff.

1. INTRODUCTION

The present research was part of a continuing investigation into the aeroelastic flutter and divergence behavior of forward swept, graphite/epoxy composite wing aircraft. The specific objectives here were to investigate experimentally and analytically, the effects of rigid body aircraft modes on the flutter and divergence of such aeroelastically tailored aircraft, and also to explore the nonlinear effects of large angles of attack and stall flutter. It was hoped thereby to obtain insight into the actual aeroelastic behavior of forward swept wing aircraft in free flight.

In previous investigations at M.I.T., the aeroelastic flutter and divergence behavior of a series of unswept and forward swept graphite/epoxy cantilever wings were investigated in a small, low speed wind tunnel. The wings were six ply graphite/epoxy plates and had strong bending-twisting coupling. By reversing the flow direction, both favorable and unfavorable angle-of-attack changes were obtained depending on the bending-twisting coupling (D_{16}) terms. This resulted in either flutter or divergence, depending on the flow direction. Also, effects of large angles of attack and stall flutter were observed experimentally on these cantilever wings. The divergence and flutter results at low angles of attack correlated well with linear theory, and indicated some beneficial effects of ply orientation on the aeroelastic behavior. See References 1 and 2.

Recently, Weisshaar and Zeiler (Reference 3) and Weisshaar,

Zeiler, Hertz and Shirk (Reference 4) pointed out some significant effects of rigid body aircraft motions in modifying the cantilever aeroelastic flutter and divergence behavior of swept forward wings. Since the bending frequency of a swept forward wing is lowered due to the approach to divergence, a new low frequency "body-freedom-flutter" which couples wing bending with aircraft rigid pitching and plunging motions becomes possible. This body-freedom-flutter may occur at speeds well below the cantilever divergence speed of the aircraft. This effect was explored on a limited basis in Reference 4 by an initial half-plane model without a canard or the rigid body plunge mode present, and gave some initial trends. Further work on a large, half plane aircraft model was done at NASA Langley by Chipman, Rauch, Rimer, Muniz, and Ricketts (References 5 and 6). Generally, however, experimental data on this effect for forward swept wing aircraft is very limited.

2. PRESENT WORK

The present investigation dealt with the effects of rigid body modes on the aeroelastic behavior of forward swept, aeroelastically tailored wings. A complete, two-sided, 30-degree forward swept wing aircraft model was constructed and mounted with low friction bearings in both pitch and plunge, inside the M.I.T. Department of Aeronautics and Astronautics low speed acoustic wind tunnel. The wind tunnel had a 1.5x2.3 m (5x7 ft.) test section and could reach velocities of 30 m/s. Figures 1,

2, and 3 show the aircraft model and its layout in the tunnel. Four different ply layup wings could be interchanges on the model, namely $[0_2/90]_s$, $[+15_2/0]_s$, $[+30_2/0]_s$ and $[-15_2/0]_s$. These wing surfaces were the same ones used in the previous cantilever tests (References 1 and 2), and thus the present tests complemented the previous cantilever tests and isolated the effects of rigid body motions.

The wind tunnel tests included measurement of the static lift and moment characteristics (done at low speeds) and the dynamic stability, flutter, and divergence testing at higher speeds. For all free flying tests, the model was set to a low trim angle of attack by adjusting the canard angle setting. Data was recorded for wing bending and wing torsion moments, aircraft angle of attack, and aircraft vertical height. Also, video movies were taken. Body-freedom-flutter was encountered for some configurations as well as bending-torsion flutter, torsional stall flutter, bending stall flutter, and a support-related dynamic instability. Figures 4 and 5 show measured static lift and moment curves, while Figures 6, 7, and 8 give examples of various flutter and dynamic instabilities encountered.

An analytical investigation was made concurrently with the experimental tests. This involved a 7-degree of freedom Rayleigh-Ritz flutter analysis using the 5 wing elastic modes of the previous cantilever wing analyses of References 1 and 2 (i.e., 1st and 2nd wing bending, 1st and 2nd wing torsion, and 1st wing chordwise bending), along with a rigid plunge mode and a rigid pitch mode. The anlaysis employed

2-dimensional strip theory with a one term lag approximation to the aerodynamic forces of the form,

$$Q_r = \frac{1}{2}\rho V^2 S[B_2 p^2 + B_1 p + B_o + B_3 p/(p+\beta)]q_s$$

and the use of augmented state variables, $y_s = pq_s/(p+\beta)$. The resulting equations led to a standard eigenvalue problem for the roots $p=\sigma+i\omega$, which were then plotted on a root locus diagram to indicate stability. A typical root locus for the $[0_2/90]_s$ wing is indicated in Figure 9. Body-freedom-flutter is indicated by the pitch mode having a positive real part σ.

Preliminary comparison of the experimental results with the linear analysis indicate good agreement for low angles of attack. The observed body-freedom-flutter, bending-torsion flutter and support-related dynamic instability were all reasonably predicted by the analyses. This latter support dynamic instability arose from the interaction of the rigid pitch mode (whose frequency increases with airspeed) with the rigid plunge mode (whose frequency is essentially constant). For the spring supported model here, the rigid pitch frequency at zero airspeed was below the rigid plunge frequency and hence a frequency coalescence dynamic instability occured over a limited range of airspeed. An additional set of experimental tests is planned with a higher rigid pitch frequency to eliminate this support instability, and to confirm the analytical predictions.

Preliminary results of the present investigation have been summarized for presentation at the 11th Annual Mechanics of Composites Review, sponsored by the Air Force Materials Laboratory, in Dayton, Ohio, October 21-23, 1985. A copy of the paper presented there is included as Appendix A of this report.

More complete results of the present investigation are currently being analyzed and will appear in a Ph.D. thesis by the second author, in the near future. This forthcoming thesis will compare experimental and analytical results of the four aeroelastically tailored wings in more detail, will compare the free flight aircraft results with the cantilever wing results, and will assess the extent of the nonlinear aeroelastic phenomena.

ACCOMPLISHMENTS

An experimental and analytical investigation was made of the aeroelastic flutter and divergence behavior of graphite/epoxy forward swept wings with rigid body pitch and plunge freedoms present. Experimental wind tunnel flutter data was obtained for a complete, two-sided 30-degree forward swept wing aircraft model mounted with low friction bearings in a low speed wind tunnel. Four different aeroelasticially tailored wing configurations were tested.

A clear picture of body-freedom-flutter was obtained experimentally, and video movies were taken. Bending-torsion

wing flutter was also observed for some of the wing configurations. These experiments appear to confirm earlier linear analytical findings.

A support-related dynamic instability was also obtained experimentally and analytically over a limited airspeed range. Analysis indicates this can be eliminated by proper choice of model support mounting frequencies.

The present investigation also has begun to explore the nonlinear aspects of flutter at higher angles of attack, where there appears a transition to nonlinear stall flutter and bending stall flutter limit cycles. These are not as well understood as the linear flutter behavior.

Preliminary results of the present investigation have been summarized for presentation at the 11th Annual Mechanics of Composites Review, sponsored by the Air Force Materials Laboratory, in Dayton, Ohio, October 21-23, 1985. See Appendix A.

More complete results of this investigation will be presented in a paper to be given at the 27th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference in San Antonio, Texas, May 19-21, 1986, entitled, "Experimental Aeroelastic Behavior of Forward Swept Graphite/Epoxy Wings with Rigid Body Freedoms".

A paper, based on earlier related work on forward swept, aeroelastically tailored cantilever wings by the principal investigator, has recently been published in the Journal of Aircraft. See Reference 2.

The present investigation has extended the experimental

base for aeroelastic tailoring with composites, and al[illegible] the corresponding theoretical analyses, should provide in[illegible] into the actual aeroelastic behavior of forward swept, [illegible] wing aircraft in free flight.

REFERENCES

1. Hollowell, S.J., and Dugundji, J., "Aeroelastic Flutter and Divergence of Stiffness Coupled, Graphite/Epoxy Cantilevered Plates", J. Aircraft, Vol. 21, No. 1, January 1984, pp. 69-76.

2. Landsberger, B., and Dugundji, J., "Experimental Aeroelastic Behavior of Unswept and Forward Swept Graphite/Epoxy Wings", J. Aircraft, Vol. 22, No. 8, August 1985, pp. 679-686.

3. Weisshaar, T.A., and Zeiler, T.A., "Dynamic Stability of Flexible Forward Swept Wing Aircraft', J. Aircraft, Vol. 21, No. 12, December 1983, pp. 1014-1020.

4. Weisshaar, T.A., Zeiler, T.A., Hertz, T.J., and Shirk, M.J., "Flutter of Forward Swept Wings, Analayses and Tests", Proceedings of the 23rd AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, New Orleans, Louisiana, May, 1982, AIAA Paper 82-0646.

5. Chipman, R., Rauch, F., Rimer, M., Muniz, B., "Body-Freedom Flutter of a 1/2 Scale Forward-Swept-Wing Model, An Experimetnal and Analytical Study", NASA CR 172-324, Grumman Aerospace Corporation, April 1984.

6. Chipman, R., Rauch, F., Rimer, M., Muniz, B., and Ricketts, R.H., "Transonic Tests of a Forward Swept Wing Configuration Exhibiting Body Freedom Flutter", Proceedings of the 26th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, Orlando, Florida, April 15-17, 1985, AIAA Paper 85-0689.

APPENDIX

Copy of paper for presentation at the, 11th Annual Mechanics of Composites Review, sponsored by the Air Force Materials Laboratory, Dayton, Ohio, October 21-23, 1985.

DYNAMICS AND AEROELASTICITY OF COMPOSITE STRUCTURES

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ABSTRACT

In previous investigations at M.I.T., the aeroelastic flutter and divergence behavior of a series of unswept and forward swept, graphite/epoxy cantilever wings were investigated in a small, low-speed wind tunnel. The wings were six-ply graphite/epoxy plates and had strong bending-twisting coupling (D_{16} terms). By adjusting the bending-torsion coupling, the divergence tendency of the forward swept, cantilever wings could be eliminated and the flutter speed raised considerably. See Refs. 1 and 2.

Presently, an investigation is being made into the effects of rigid body aircraft modes on the aeroelastic behavior of forward swept wings. It has recently been pointed out in Refs. 3 and 4, that for forward swept wings, the rigid body modes may possibly couple with the wing bending mode to cause a new low frequency "body-freedom-flutter." Accordingly, a complete, two-sided 30° forward swept wing aircraft model was constructed and mounted with low friction bearings in both pitching and translation, inside the M.I.T. low speed acoustic wind tunnel. The wind tunnel had a 1.5 x 2.3 m (5 x 7 ft.) test section and could reach velocities of 30 m/s. Four different ply layup wings could be interchanged on the model, namely $[0_2/90]_s$, $[+15_2/0]_s$, $[+30_2/0]_s$ and $[-15_2/0]_s$. These wing surfaces were the same ones used in the previous cantilever tests (Refs. 1 and 2), and thus the present tests complemented the previous cantilever tests and isolated the effects of rigid body motions.

The wind tunnel tests included measurement of the static lift and moment characteristics (done at low speeds) and the dynamic stability, flutter, and divergence testing at higher speeds. For all free flying tests, the model was set to a low trim angle of attack, and aircraft vertical height. Also, TV movies were taken. Body-freedom-flutter was encountered for some configurations as well as torsional stall flutter, bending stall flutter, and dynamic instability. Examples are given of various flutter and dynamic instabilities encountered. These experimental tests, along with the previous cantilever wing tests and with corresponding analytical analyses, should provide insight into the actual aeroelastic behavior of forward swept wing aircraft in free flight.

REFERENCES

1. Hollowell, S.J., and Dugundji, J., "Aeroelastic Flutter and Divergence of Stiffness Coupled, Graphite/Epoxy Cantilevered Plates," J. Aircraft, Vol. 21, No. 1, January 1984, pp. 69-76.

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3. Weisshaar, T.A., Zeiler, T.A., Hertz, T.J., and Shirk, M.J., "Flutter of Forward Swept Wings, Analyses and Tests," Proceedings of the 23rd AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, New Orleans, Louisiana, May, 1982, AIAA Paper 82-0646.

4. Chipman, R., Rauch, F., Rimer, M., Muniz, B., and Ricketts, R.H., "Transonic Tests of a Forward Swept Wing Configuration Exhibiting Body Freedom Flutter," Proceedings of the 26th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, Orlando, Florida, April 15-17, 1985, AIAA Paper 85-0689.

DYNAMICS AND AEROELASTICITY OF
COMPOSITE STRUCTURES

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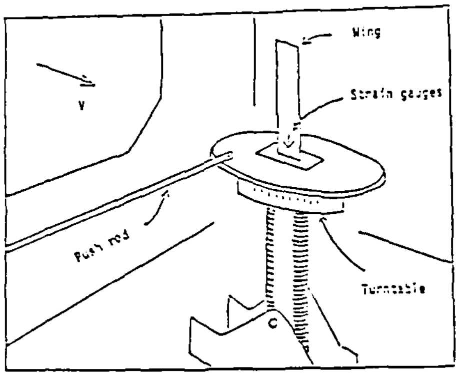
OBJECTIVES

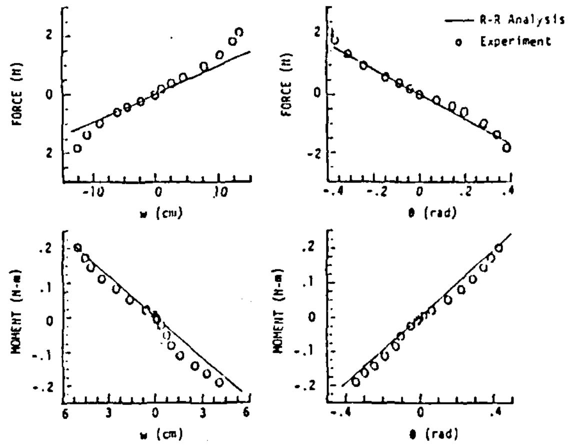
- Investigate the effects of rigid body aircraft modes on the flutter and divergence of forward swept, graphite/epoxy wings
- Explore nonlinear effects of large angle of attack and stall flutter
- Obtain insight into actual aeroelastic behavior of forward swept, aeroelastically tailored aircraft in free flight

APPROACH

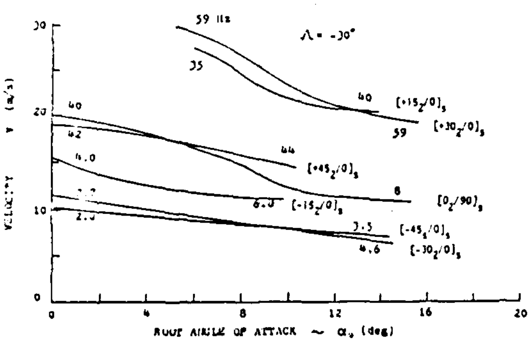
- Build complete, two-sided 30° forward swept wing aircraft model with rigid pitch and rigid translation capability
- Obtain experimental data on model in low speed wind tunnel, and compare with corresponding cantilever wing tests
- Perform analytical flutter and divergence calculations including effects of rigid body modes



Test Set-Up in Tunnel (Cantilever Wing)

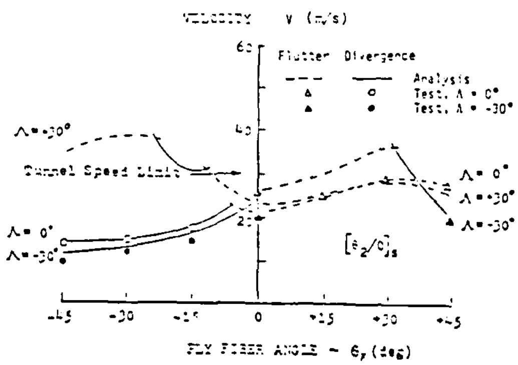


Structural Deflections of $[+30_2/0]_s$ Wing



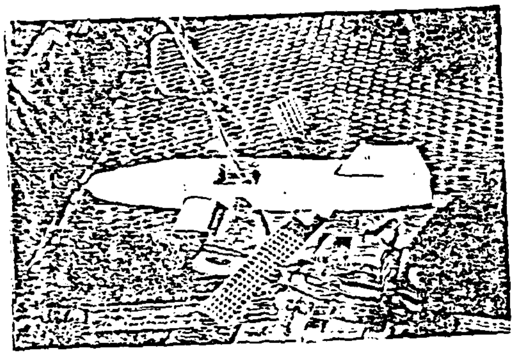
Experimental Flutter and Divergence Boundaries, Λ = - 30°

(Cantilever Wing)

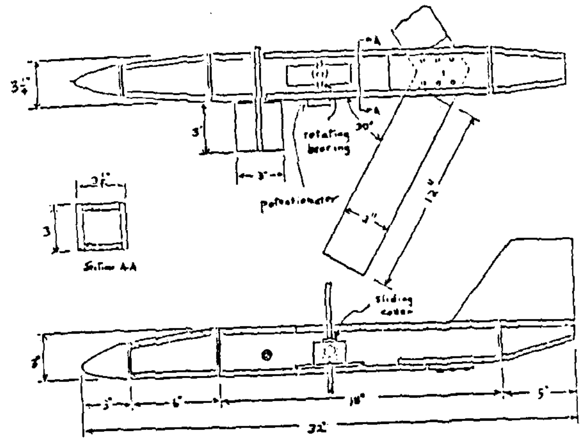


Flutter and Divergence at Low Root Analyses, α_o

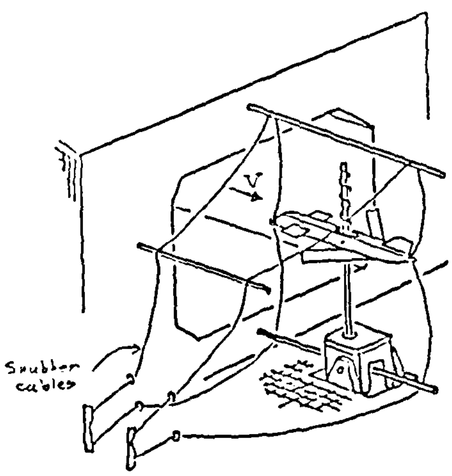
(Cantilever Wing)



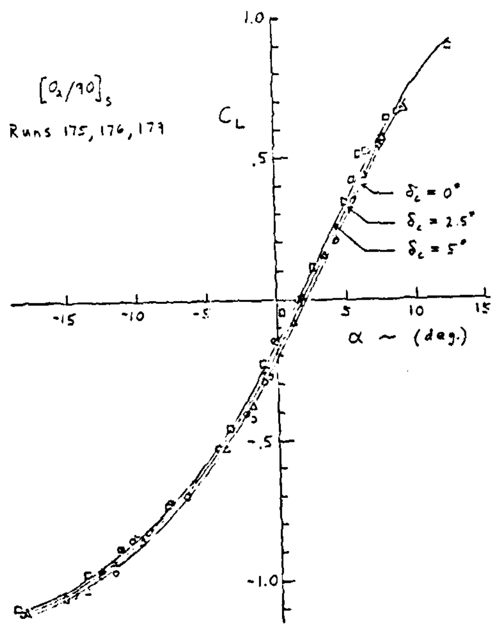
Forward Swept Wing Model



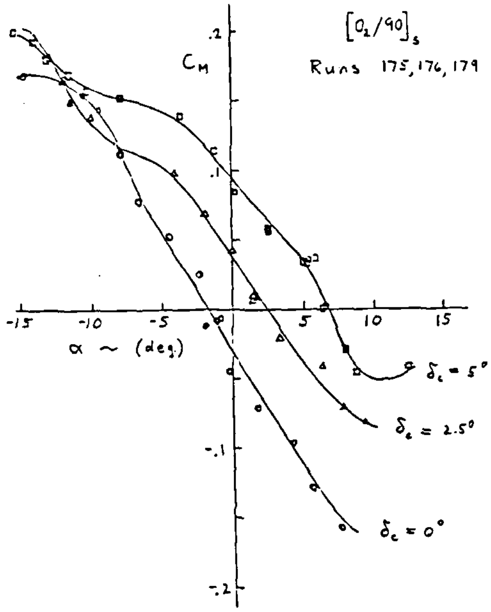
Forward Swept Wing Model



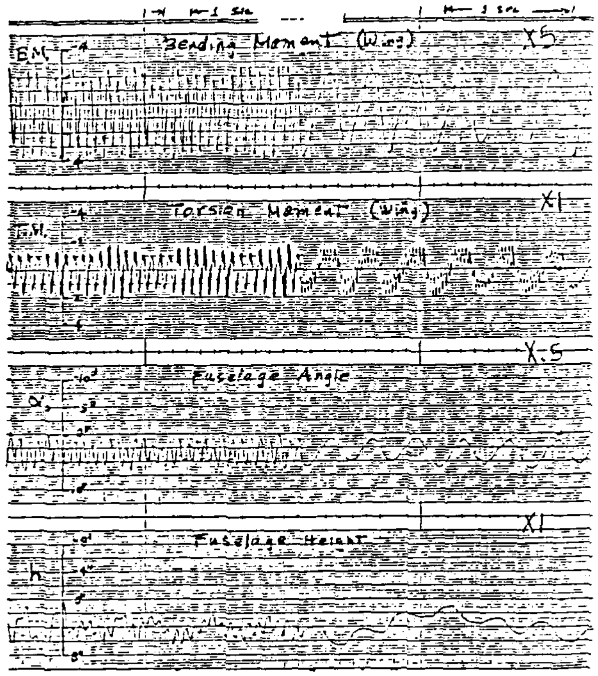
M.I.T. Acoustic Tunnel Test Set-Up



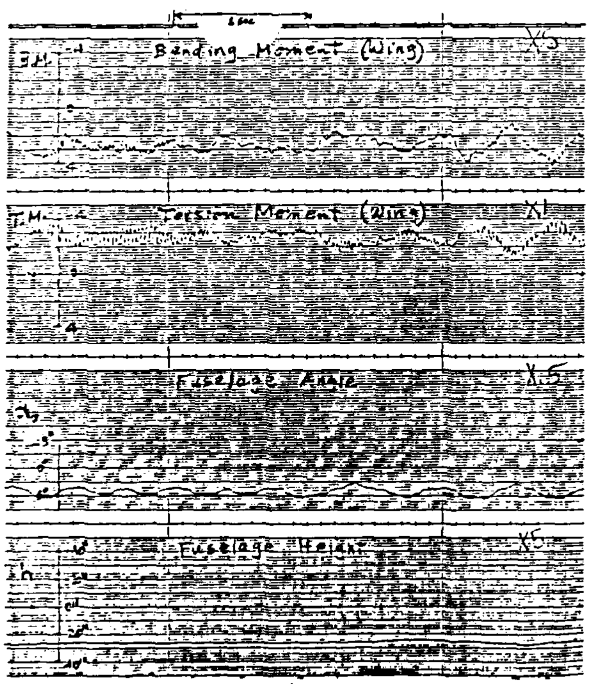
Static Lift Curves



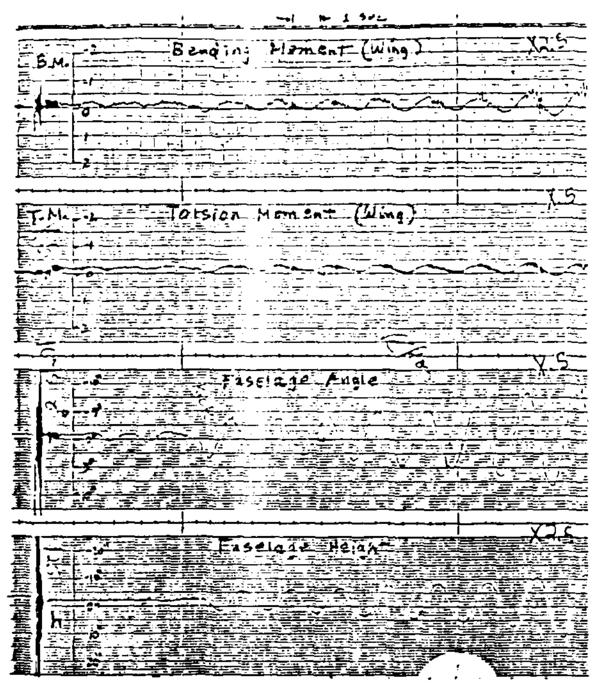
Static Moment Curves



Flutter Record, Run #180, $[0_2/90]_s$, δ_c = 2.5°, V = 20 m/s

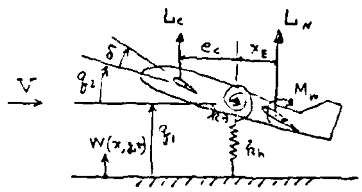


Torsional Stall Flutter, Run #198, $[15_2/0]_s$, δ_c = 2.5°, V = 28 m/s



Dynamic Instability, Run #185, $[0_2/90]_s$, δ_c = 0°, V = 10 m/s

Theoretical Analysis



$$w(x,y,t) = \sum_{i=1}^{7} \gamma_i(x,y)\, q_i(t)$$

q_1 = Rigid Transl
q_2 = Rigid Pitch
q_3 = 1st Cantil Bend
q_4 = 2nd " "
q_5 = 1st Torsion
q_6 = 2nd "
q_7 = 1st Chordwise

$$T = \frac{1}{2}\iint m\,\dot{w}^2\,dx\,dy = \frac{1}{2}\sum^{i}\sum^{j} M_{ij}\,\dot{q}_i\,\dot{q}_j$$

$$U = \frac{1}{2}\iint\left\{D_{11} w_{xx}^2 + \cdots\right\}dx\,dy + \frac{1}{2}k_h q_1^2 + \frac{1}{2}k_\theta q_2^2 = \frac{1}{2}\sum^{i}\sum^{j} K_{ij}\, q_i\, q_j$$

$$\delta W = \sum^{i} Q_i\,\delta q_i$$

Equations of Motion

$$\underset{\sim}{M}\,\ddot{\underset{\sim}{q}} + \underset{\sim}{K}\,\underset{\sim}{q} = \underset{\sim}{Q}_{Aero}$$

Vibrations : $q_i = \bar{q}_i e^{i\omega t}$

$$\left[-\omega^2 \underset{\sim}{M} + \underset{\sim}{K}\right]\underset{\sim}{q} = 0 \longrightarrow \text{Solve } \omega,\ \underset{\sim}{q}$$

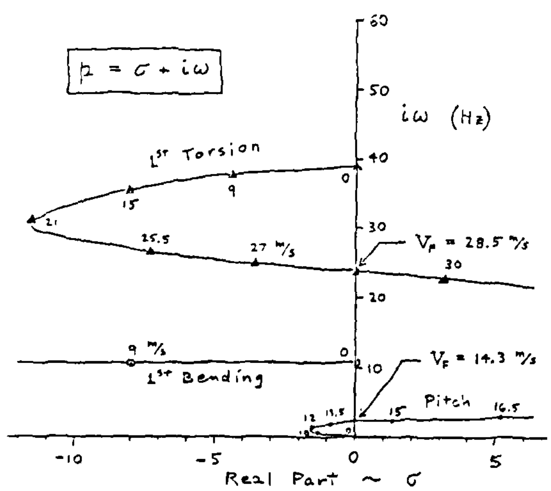
Flutter : $q_i = \bar{q}_i e^{pt}$

$$\left[p^2\underset{\sim}{M} + \underset{\sim}{K} - \frac{1}{2}\rho V^2 S\left(\underset{\sim}{B}_2 p^2 + \underset{\sim}{B}_1 p + \underset{\sim}{B}_0 + \underset{\sim}{G}_1 \frac{p}{p+\gamma_1}\right)\right]\underset{\sim}{q} = 0$$

$$\longrightarrow \text{Solve } p,\ \underset{\sim}{q}$$

Divergence : $q_i = \bar{q}_i$

$$\left[\underset{\sim}{K} - \frac{1}{2}\rho V^2 S\,\underset{\sim}{B}_0\right]\underset{\sim}{q} = 0 \longrightarrow \text{Solve } V,\ \underset{\sim}{q}.$$



Theoretical Stability Plot, $[0_2/90]_s$

CURRENT STATUS

- Currently, analyzing results of model wind tunnel tests
- Observed body-freedom-flutter, torsional stall flutter, dynamic instability, nonlinear phenomena
- Currently, performing analytical flutter and divergence analyses to assess experimental results, compare with cantilever results, and assess extent of nonlinear phenomena

FIGURES

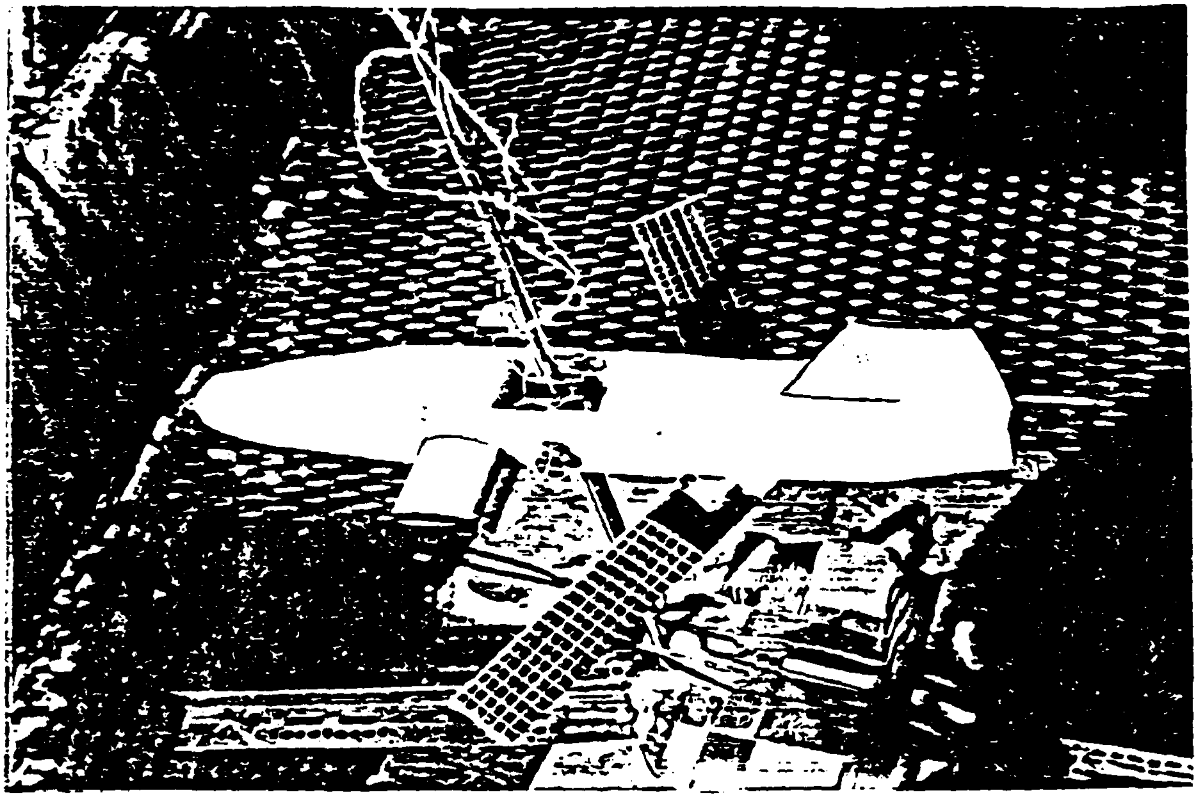


Figure 1 - Forward Swept Wing Model

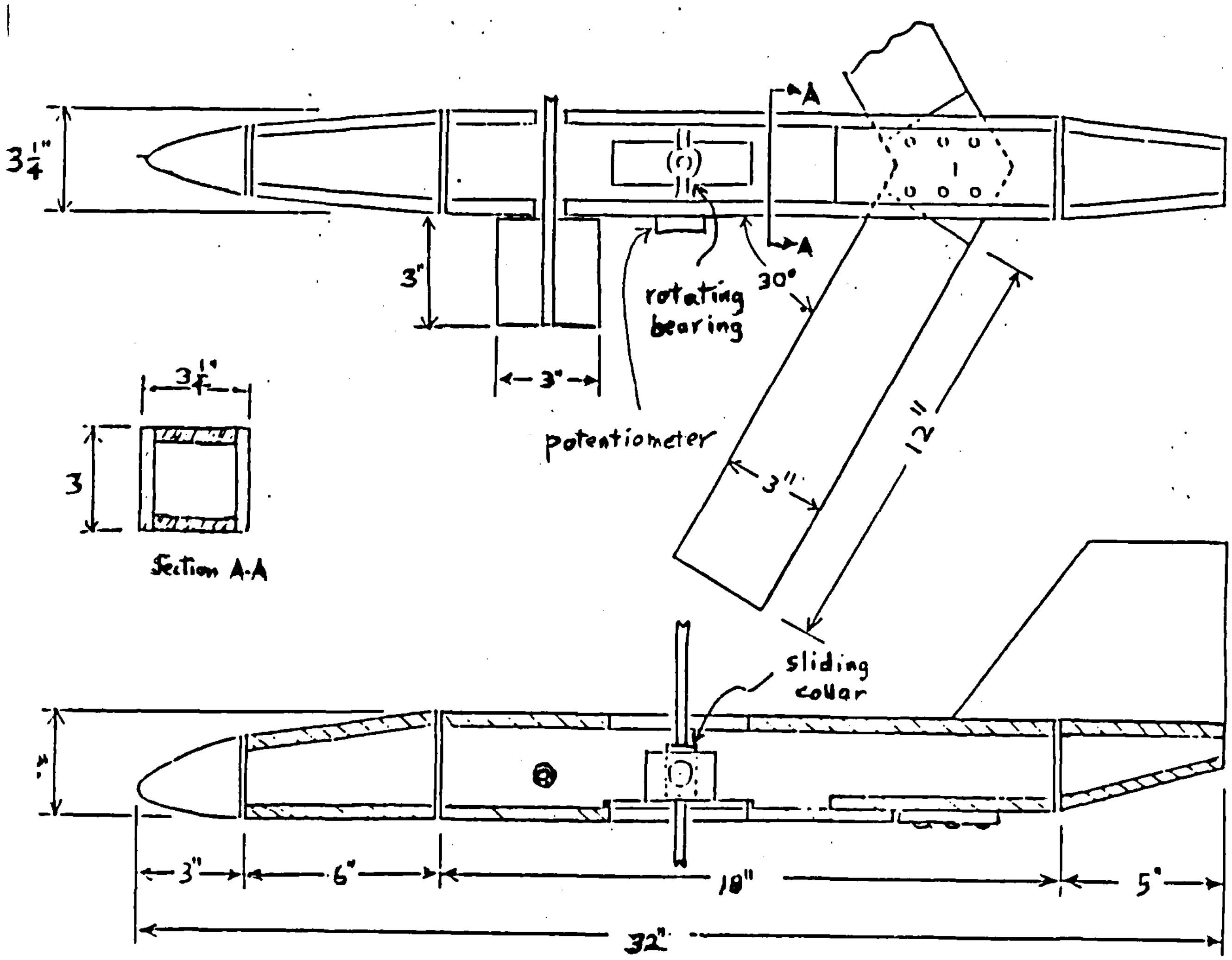


Figure 2 - Forward Swept Wing Model

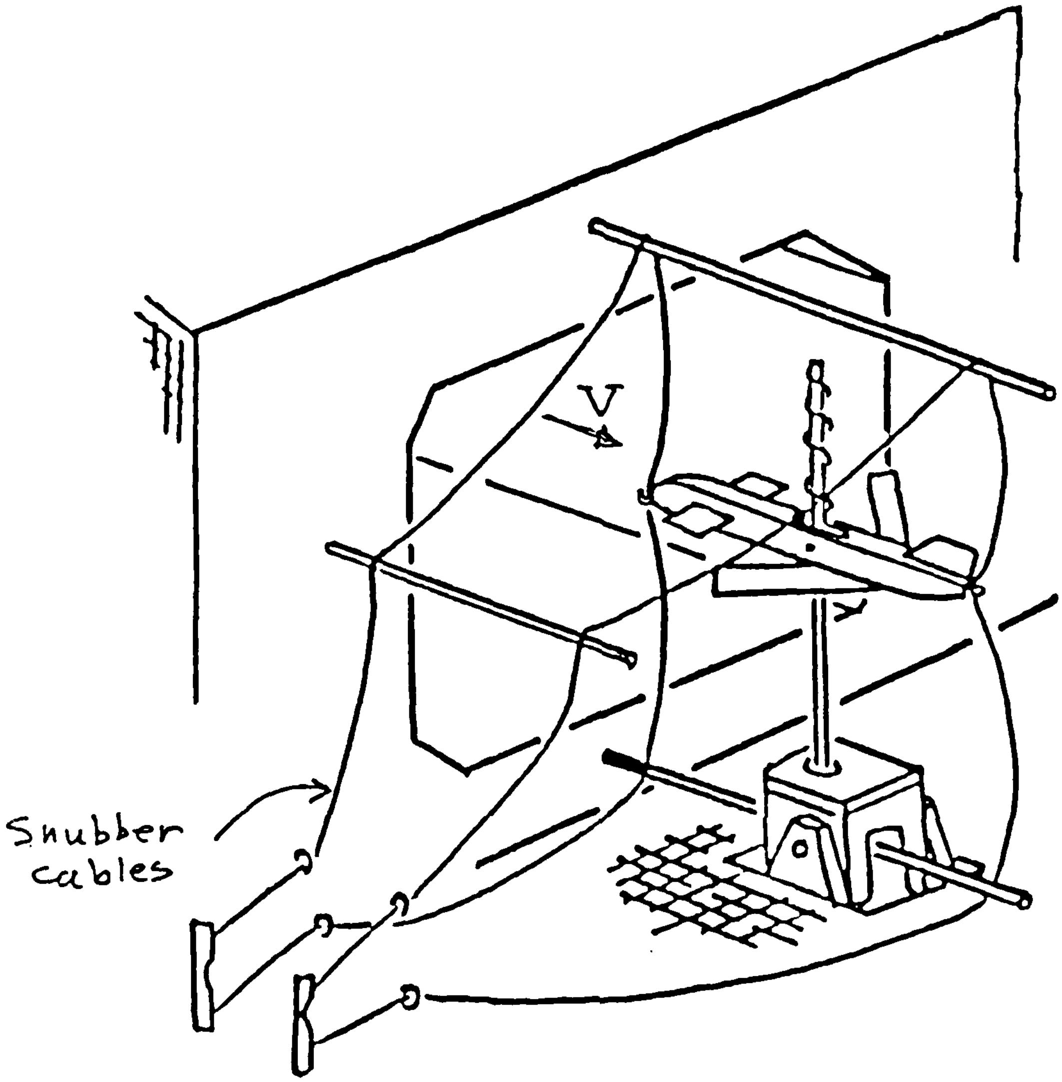


Figure 3 - M.I.T. Acoustic Tunnel Test Set-Up

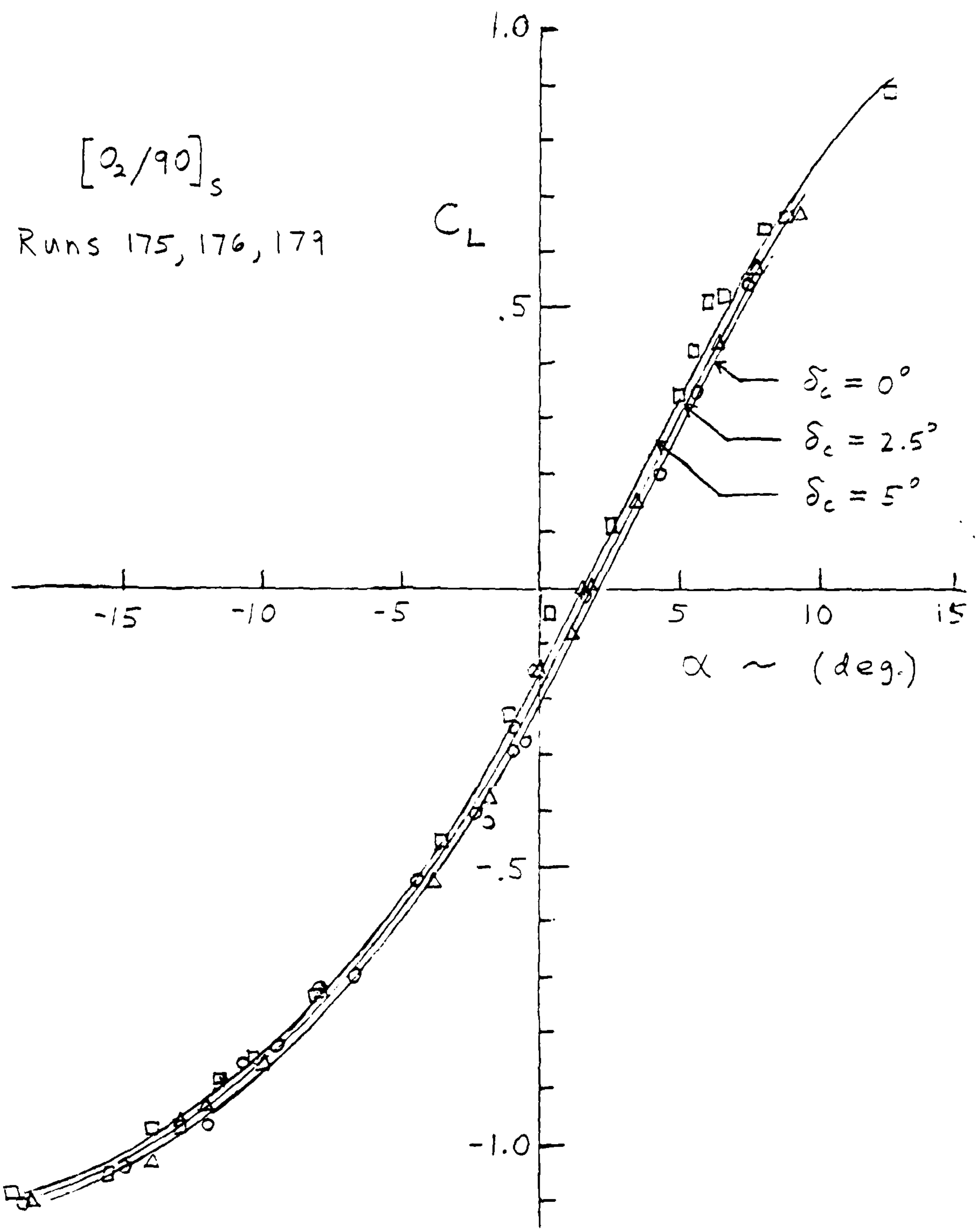


Figure 4 - Static Lift Curves

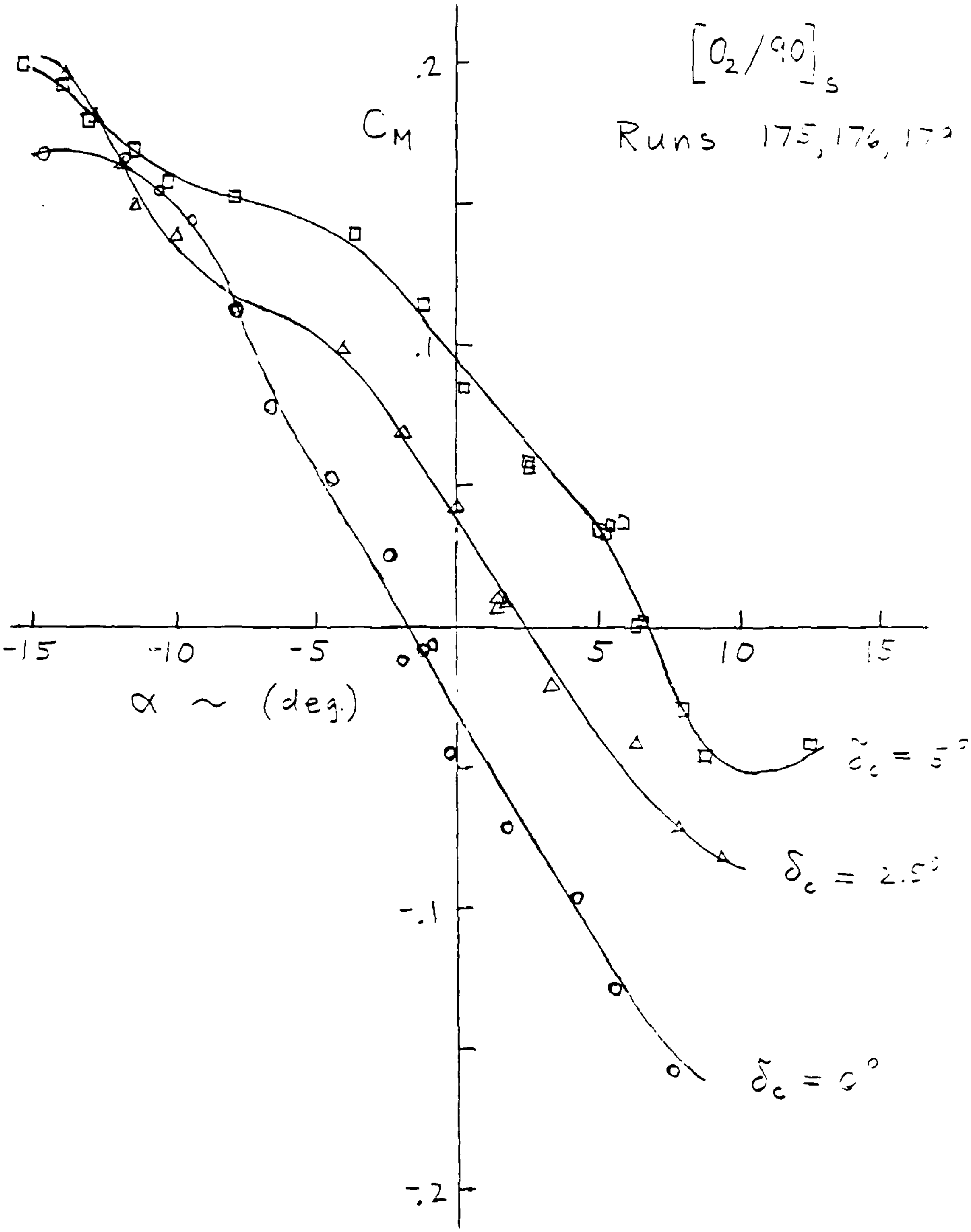


Figure 5 - Static Moment Curves

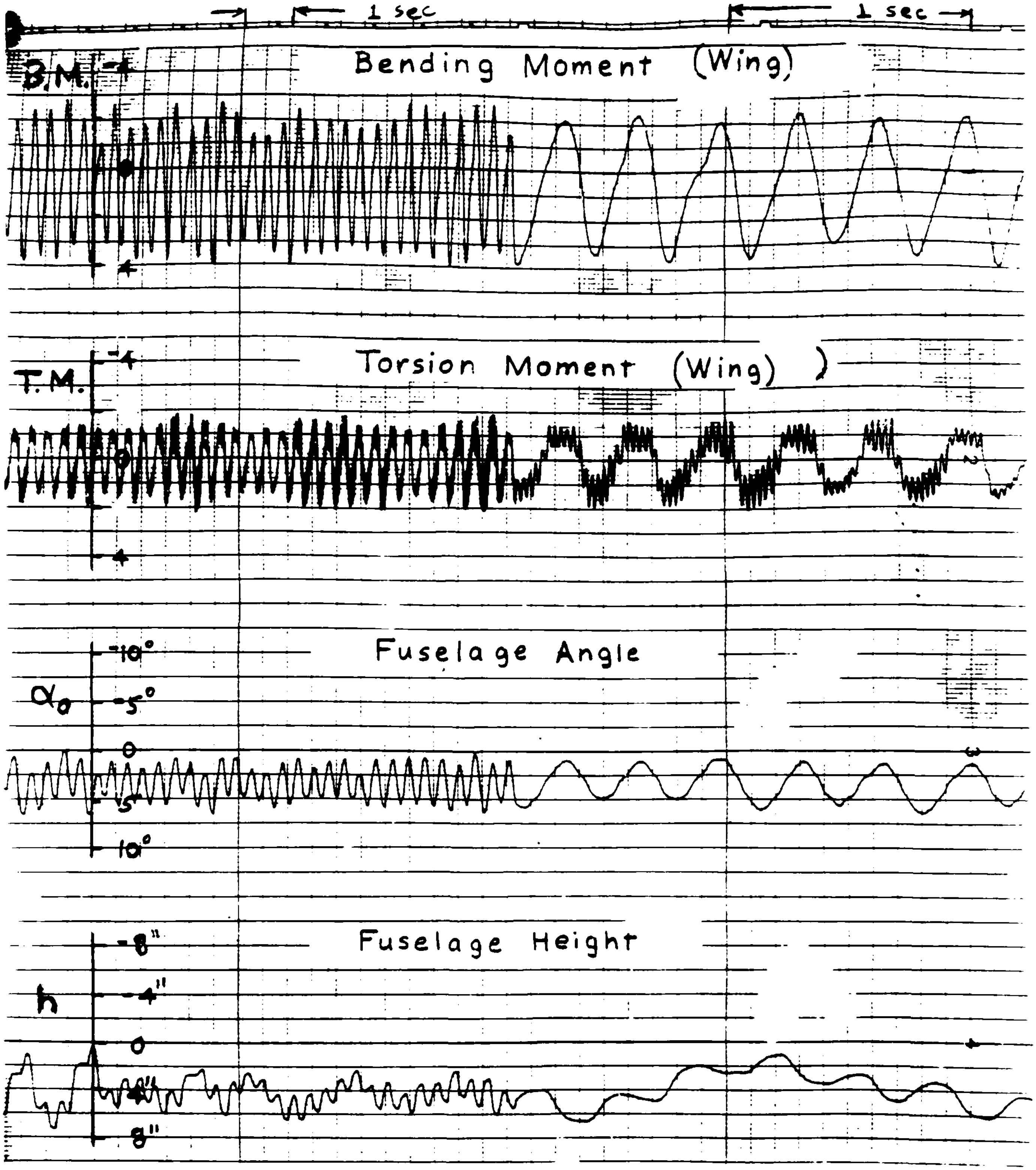


Figure 6 - Flutter Record, Run #130, $[0_2/90]_S$, δ_C = 2.5°, V = 20 m/s

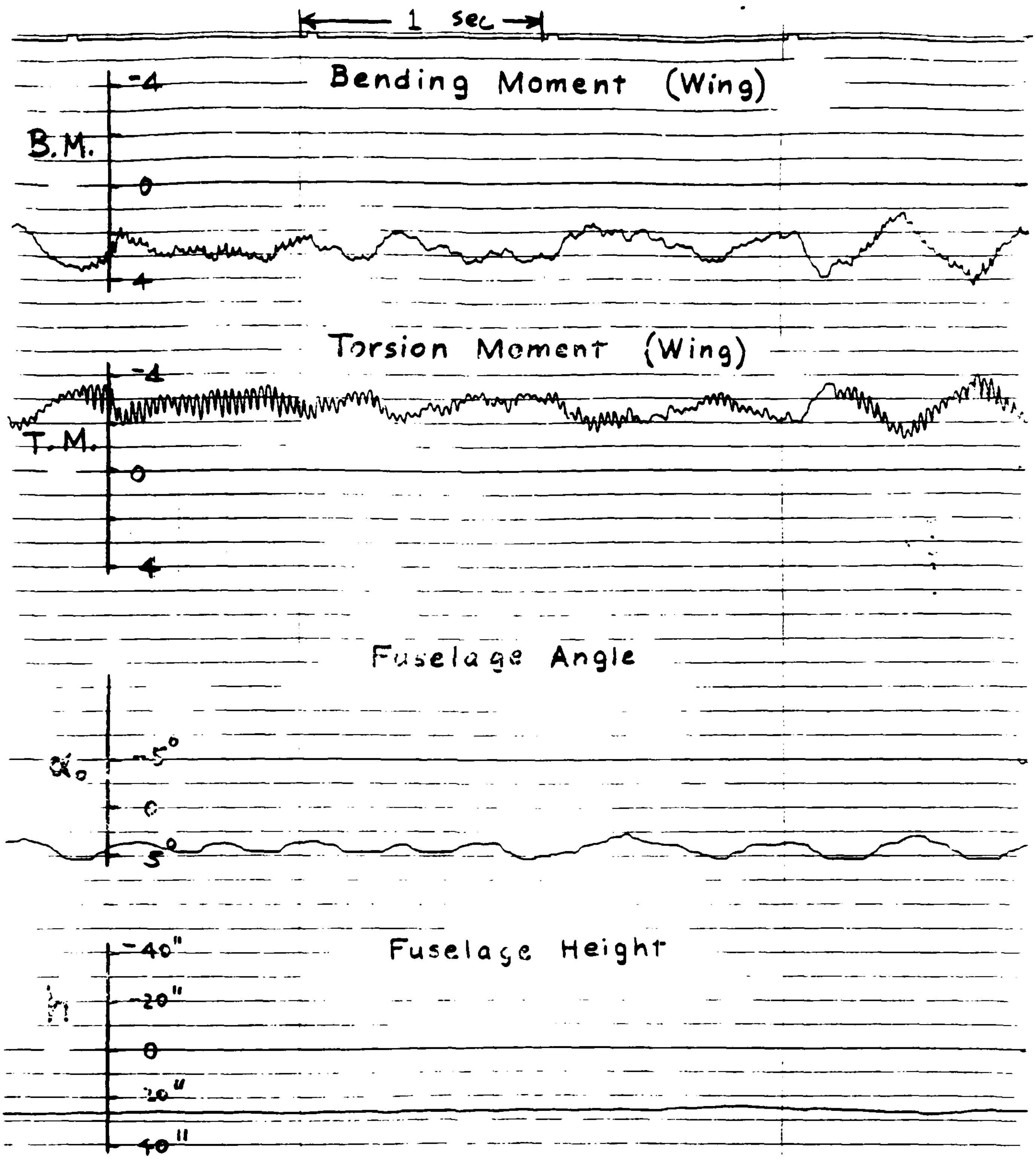


Figure 7 - Torsional Stall Flutter, Run #198, $[15_2/0]_S$, $\delta_C = 2.5°$, $V = 28$ m/s

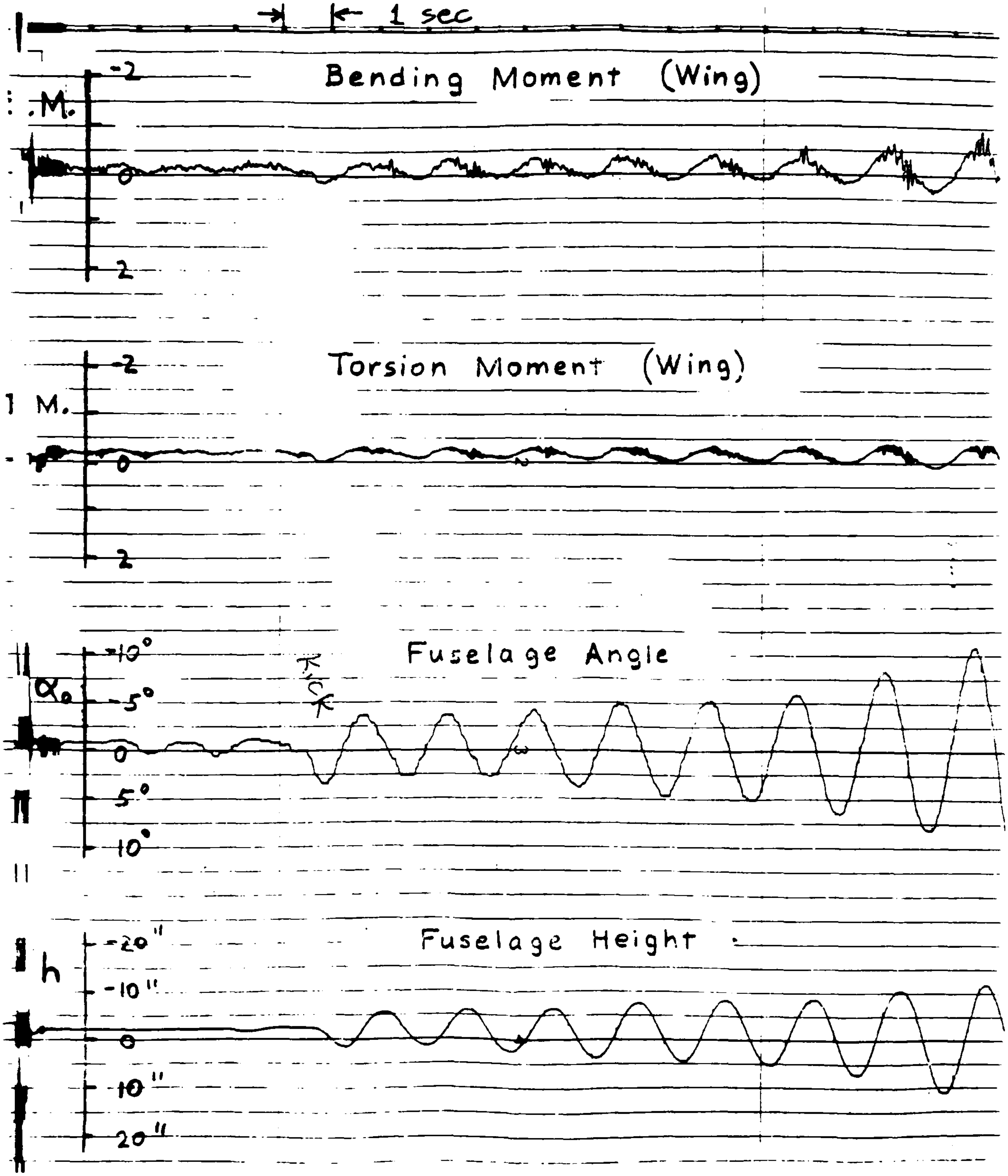


Figure 8 - Dynamic Instability, Run #185, $[0_2/90]_s$, $\delta_c = 0°$, V = 10 m/s

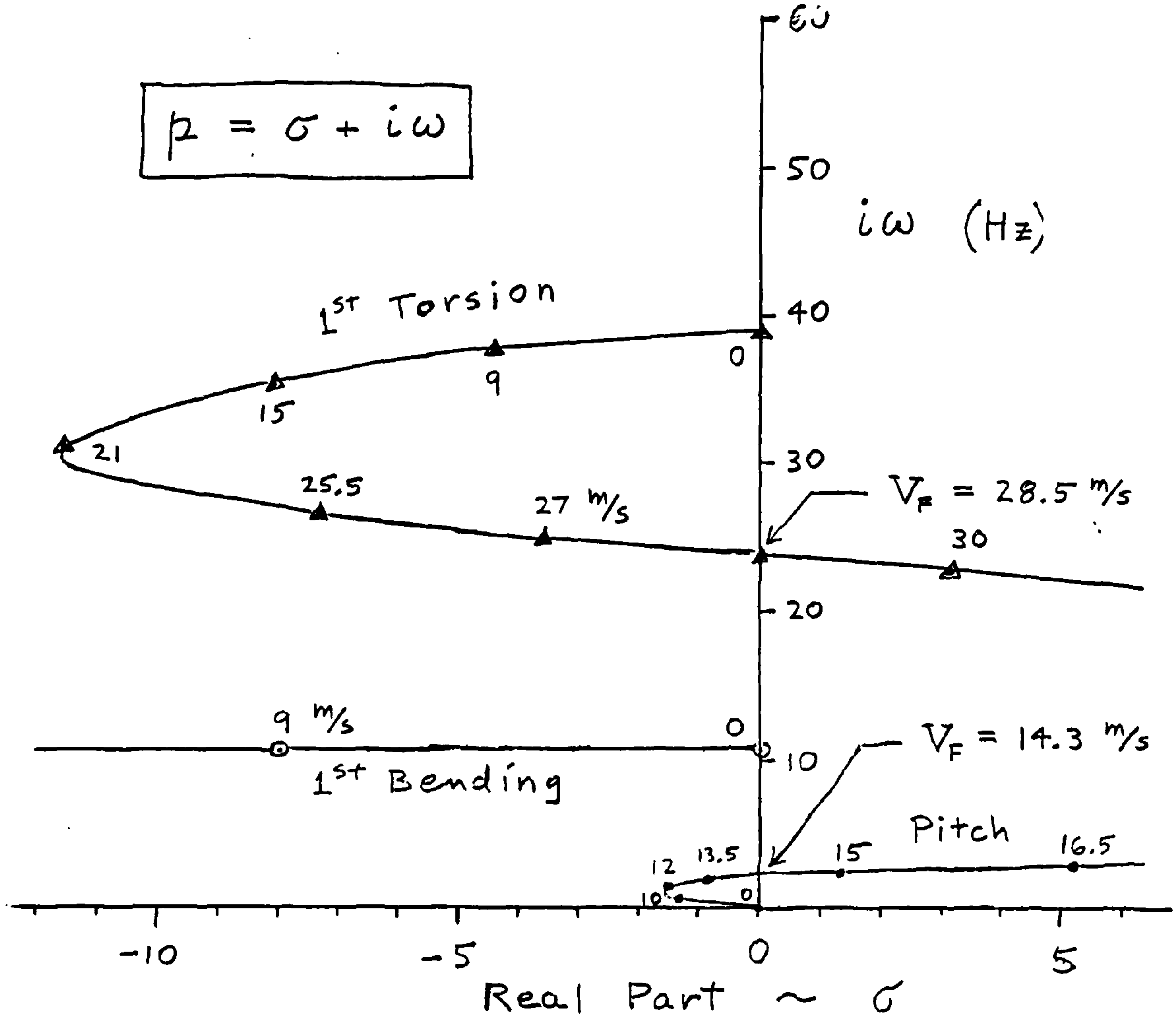


Figure 9 - Theoretical Stability Plot, $[0_2/90]_s$

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